

Connecting B_d and B_s decays through QCD factorisation and flavour symmetries

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Abstract. We analyse $B_{d,s} \rightarrow K^{(*)0} K^{(*)0}$ modes within the SM, relating them in a controlled way through $SU(3)$ -flavour symmetry and QCD-improved factorisation. We propose a set of sum rules for such penguin-mediated decays to constrain some CKM angles. We determine $B_s \rightarrow KK$ branching ratios and CP-asymmetries as functions of $A_{dir}(B_d \rightarrow K^0 \bar{K}^0)$. Applying the same techniques to $B_{d,s} \rightarrow K^{*0} K^{*0}$, we outline strategies to determine the B_s mixing angle.

Non-leptonic two-body B_d - and B_s -decays provide many interesting ways of testing the CKM mechanism of CP-violation, but the effects of strong interaction often hinder quantitative predictions. The relevant hadronic quantities can be estimated through flavour symmetries, such as U -spin, but with a sizeable uncertainty. QCD factorisation (QCDF) provides a complementary tool, specially for short distances, but this expansion in α_s and $1/m_b$ cannot predict some $1/m_b$ -suppressed long-distance effects. Recently, it was proposed to improve theoretical predictions by combining QCDF and U -spin in particular classes decays [3, 4].

1. Sum rules

In the Standard Model (SM), we can always split a B -decay amplitude into its tree and penguin contributions $\bar{A} \equiv A(\bar{B}_q \rightarrow M\bar{M}) = \lambda_u^{(q)} T_M^q + \lambda_c^{(q)} P_M^q$ according to the CKM factors $\lambda_p^{(q)} = V_{pb} V_{pq}^*$. One can compute these contributions for $\bar{B}_s \rightarrow K^0 \bar{K}^0$ within QCDF [1, 2]:

$$\hat{T}^{s0} = \bar{\alpha}_4^u - \frac{1}{2} \bar{\alpha}_{4EW}^u + \bar{\beta}_3^u + 2\bar{\beta}_4^u - \frac{1}{2} \bar{\beta}_{3EW}^u - \bar{\beta}_{4EW}^u, \quad (1)$$

$$\hat{P}^{s0} = \bar{\alpha}_4^c - \frac{1}{2} \bar{\alpha}_{4EW}^c + \bar{\beta}_3^c + 2\bar{\beta}_4^c - \frac{1}{2} \bar{\beta}_{3EW}^c - \bar{\beta}_{4EW}^c, \quad (2)$$

where $\hat{P}^{sC} = P^{sC}/A_{KK}^s$, $\hat{T}^{sC} = T^{sC}/A_{KK}^s$ and $A_{KK}^q = M_{B_q}^2 F_0^{\bar{B}_q \rightarrow K}(0) f_K G_F / \sqrt{2}$. β 's denote weak-annihilation contributions whereas α 's collect remaining terms (vertex and hard-spectator interactions). A similar structure occurs for the tree and penguin contributions T^{d0} and P^{d0} for $\bar{B}_d \rightarrow K^0 \bar{K}^0$, and for longitudinally polarised $K^{*0} \bar{K}^{*0}$ [2, 4]. As exemplified in eqs. (1)-(2), for penguin-mediated decays, T and P are actually generated only by penguin topologies, and thus share the same long-distance dynamics: the difference comes from the (u or c) quark running in the loops [3]. Thus, $\Delta = T - P$ is mildly affected by annihilation and hard-spectator contributions, and it can be computed with smaller uncertainties than T or P individually within

QCDF: $\Delta^{d0} \equiv T^{d0} - P^{d0} = A_{KK}^d[\alpha_4^u - \alpha_4^c + \beta_3^u - \beta_3^c + 2\beta_4^u - 2\beta_4^c]$. The $1/m_b$ suppressed long-distance dynamics, modelled in QCDF, cancels in the differences between u and c contributions.

These theoretically well-behaved differences are related to the CP-averaged branching ratio BR and the direct and mixed CP-asymmetries \mathcal{A}_{dir} and \mathcal{A}_{mix} (see [3, 4] for the exact definitions). For a B_d meson decaying through a $b \rightarrow D$ process ($D = d, s$) [such as $B_d \rightarrow K^{*0} \bar{K}^{*0}$ or $B_d \rightarrow \phi \bar{K}^{*0}$ (with a subsequent decay into a CP eigenstate)], one extracts α [5] and β from:

$$\sin^2 \alpha = \widetilde{BR}/(2|\lambda_u^{(D)}|^2|\Delta|^2) \left(1 - \sqrt{1 - (\mathcal{A}_{\text{dir}})^2 - (\mathcal{A}_{\text{mix}})^2}\right), \quad (3)$$

$$\sin^2 \beta = \widetilde{BR}/(2|\lambda_c^{(D)}|^2|\Delta|^2) \left(1 - \sqrt{1 - (\mathcal{A}_{\text{dir}})^2 - (\mathcal{A}_{\text{mix}})^2}\right), \quad (4)$$

where \widetilde{BR} is the CP-averaged branching ratio, up to a trivial kinematic factor [4]. Similar identities can be used for a B_s meson decaying through $b \rightarrow D$ ($D = d, s$) [such as $B_s \rightarrow K^{*0} \bar{K}^{*0}$ or $B_s \rightarrow \phi \bar{K}^{*0}$] to extract the angles β_s and γ , assuming no New Physics in the decay.

2. $B_d \rightarrow K^0 \bar{K}^0$ and $B_s \rightarrow K^0 \bar{K}^0$

These penguin-mediated decays are related by U -spin, with a small breaking: few processes (weak annihilation and spectator interaction) probe the spectator quark, as confirmed by QCDF:

$$P^{s0} = fP^{d0} \left[1 + (A_{KK}^d/P^{d0}) \left\{ \delta\alpha_4^c - \delta\alpha_{4EW}^c/2 + \delta\beta_3^c + 2\delta\beta_4^c - \delta\beta_{3EW}^c/2 - \delta\beta_{4EW}^c \right\} \right], \quad (5)$$

$$T^{s0} = fT^{d0} \left[1 + (A_{KK}^d/T^{d0}) \left\{ \delta\alpha_4^u - \delta\alpha_{4EW}^u/2 + \delta\beta_3^u + 2\delta\beta_4^u - \delta\beta_{3EW}^u/2 - \delta\beta_{4EW}^u \right\} \right], \quad (6)$$

These ratios involve the U -spin breaking differences $\delta\alpha_i^p \equiv \bar{\alpha}_i^p - \alpha_i^p$ (id. for β). Apart from the ratio $f = M_{B_s}^2 F_0^{\bar{B}_s \rightarrow K}(0)/[M_{B_d}^2 F_0^{\bar{B}_d \rightarrow K}(0)]$, U -spin arises only through $1/m_b$ -suppressed terms in which most long-distance effects have cancelled out. In agreement with this observation, QCDF [2] yields tiny uncertainties: $|P^{s0}/(fP^{d0}) - 1| \leq 3\%$ and $|T^{s0}/(fT^{d0}) - 1| \leq 3\%$. These relations depend much less on the QCDF model for $1/m_b$ -suppressed contributions than the predictions for individual tree or penguin contributions, and thus they provide an interesting alternative to a pure QCDF computation. One can also relate the penguin contributions to $\bar{B}_d \rightarrow K_0 \bar{K}_0$ and $\bar{B}_s \rightarrow K^+ K^-$ (see [3] for the treatment of tree contributions).

For $B_d \rightarrow K^0 \bar{K}^0$, the branching ratio $BR^{d0} = (0.96 \pm 0.25) \cdot 10^{-6}$ [6] has been measured. If A_{dir}^{d0} becomes available, we may exploit the theoretically well-controlled value of $\Delta_d \equiv T^{d0} - P^{d0}$ to get the two moduli and the relative phase of T^{d0} and P^{d0} from BR^{d0} , A_{dir}^{d0} and Δ_d . Then we can use the previous bounds to compute the tree and penguin contributions for $B_s \rightarrow KK$ decays, leading to the SM predictions for the corresponding observables (see Table I in ref. [3]): $Br(B_s \rightarrow K^0 \bar{K}^0) = (18 \pm 7 \pm 4 \pm 2) \cdot 10^{-6}$ and $Br(B_s \rightarrow K^+ \bar{K}^-) = (20 \pm 8 \pm 4 \pm 2) \cdot 10^{-6}$, the latter being in very good agreement with the latest CDF measurement [7].

3. $B_d \rightarrow K^{*0} \bar{K}^{*0}$ and $B_s \rightarrow K^{*0} \bar{K}^{*0}$

We focus on observables for mesons with a longitudinal polarisation which can be measured experimentally and predicted theoretically with a good accuracy. $B_s \rightarrow K^{*0} \bar{K}^{*0}$ is in principle a clean mode to extract the mixing angle ϕ_s . An expansion in powers of $\lambda_u^{(s)}/\lambda_c^{(s)}$ yields

$$\mathcal{A}_{\text{mix}}^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0}) \simeq \sin \phi_s + 2 \left| \frac{\lambda_u^{(s)}}{\lambda_c^{(s)}} \right| \text{Re} \left(\frac{T^{s0*}}{P^{s0*}} \right) \sin \gamma \cos \phi_s + \dots = \sin \phi_s + \Delta S(B_s \rightarrow K^{*0} \bar{K}^{*0}) \quad (7)$$

A significant value of T^{s0*}/P^{s0*} could spoil the extraction of $\sin \phi_s$. One can use our knowledge on $T^{s0*} - P^{s0*}$ to bound $\Delta S(B_s \rightarrow K^{*0} \bar{K}^{*0})$, as illustrated in fig. 1.

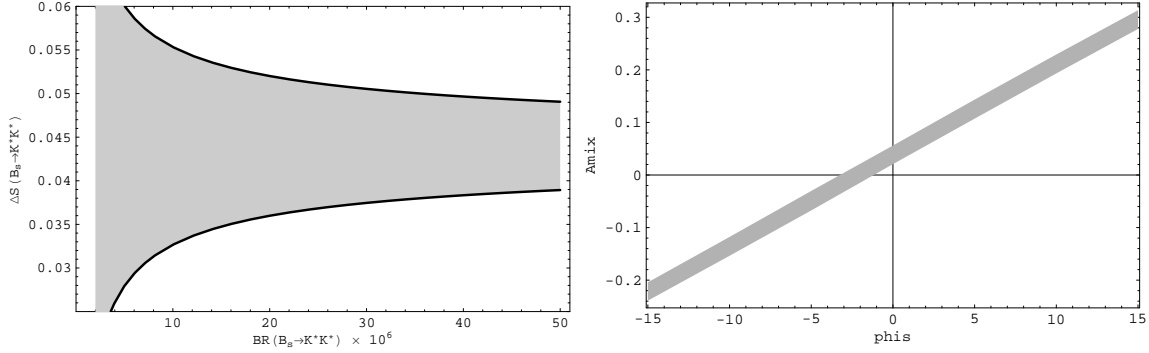


Figure 1. The absolute bounds on $\Delta S(B_s \rightarrow K^{*0} \bar{K}^{*0})$ as functions of $BR^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0})$ (on the left) and the relation between $A_{\text{mix}}^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0})$ and the $B_s - \bar{B}_s$ mixing angle ϕ_s (on the right), assuming $BR^{\text{long}}(B_d \rightarrow K^{*0} \bar{K}^{*0}) \geq 5 \times 10^{-7}$ and $\gamma = 62^\circ$.

One can also relate the observables in $B_{d,s} \rightarrow K^{*0} \bar{K}^{*0}$ through the same combination of U -spin symmetry and QCDF. Once again, U -spin is mainly broken through the ratio of relevant form factors f^* , whereas most of the long-distance annihilation and spectator scattering contributions cancel in $P^{s0*}/(f^* P^{d0*})$ and $T^{s0*}/(f^* T^{d0*})$. Indeed, QCDF yields $|P^{s0*}/(f^* P^{d0*}) - 1| \leq 12\%$ and $|T^{s0*}/(f^* T^{d0*}) - 1| \leq 15\%$, which can be exploited to predict $B_s \rightarrow K^{*0} \bar{K}^{*0}$ observables. The ratio of branching ratios $BR^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0})/BR^{\text{long}}(B_d \rightarrow K^{*0} \bar{K}^{*0})$ and the asymmetries as predicted in the SM turn out to be quite insensitive to the exact value of $BR^{\text{long}}(B_d \rightarrow K^{*0} \bar{K}^{*0})$ as long as $BR^{\text{long}}(B_d \rightarrow K^{*0} \bar{K}^{*0}) \geq 5 \times 10^{-7}$:

$$BR^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0})/BR^{\text{long}}(B_d \rightarrow K^{*0} \bar{K}^{*0}) = 17 \pm 6 \quad (8)$$

$$\mathcal{A}_{\text{dir}}^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0}) = 0.000 \pm 0.014 \quad \mathcal{A}_{\text{mix}}^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0}) = 0.004 \pm 0.018 \quad (9)$$

If one assumes no New Physics in the decay $B_s \rightarrow K^{*0} \bar{K}^{*0}$, this method relates directly $\mathcal{A}_{\text{mix}}^{\text{long}}(B_s \rightarrow K^{*0} \bar{K}^{*0})$ and ϕ_s as indicated in fig.1.

4. Conclusions

We have combined experimental data, flavour symmetries and QCDF to gain control on penguin-mediated $B_{d,s}$ decays. The difference between tree and penguin contributions can be assessed with a good accuracy. The U -spin breaking between B_d and B_s modes arises in few factorisable corrections (ratio of form factors) and non-factorisable corrections (weak annihilation and spectator scattering). QCDF confirms these expectations, and provides predictions with a limited model dependence on $1/m_b$ -suppressed long-distance contributions. We outlined the implications for $B_s \rightarrow K \bar{K}$ in pseudoscalar and vector channels. Sizeable NP effects would break these SM correlations between B_d and B_s decays, leading to departure from our predictions.

Acknowledgments

Work supported in part by EU Contract No. MRTN-CT-2006-035482, “FLAVIANet”.

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